**Thermodynamics of Impacts onto Icy Mixtures: Peak and Post-shock Temperature Measurements in an Ice-Sand Mixture.** R. G. Kraus and S. T. Stewart, Harvard University, Department of Earth and Planetary Sciences, 20 Oxford Street, Cambridge, MA 02138, U.S.A. (rkraus@fas.harvard.edu)

**Introduction:** Shock processes in heterogeneous materials is a challenging aspect of impact cratering studies. Understanding the equipartition of energy in shocked mixtures of widely varying impedence is necessary to predict a wide range of phenomena, including phase changes, post-shock temperatures, and chemical reactions. Here, we present the results from shock pyrometry experiments on a mixture of sand and $H_2O$ ice, which constitute a portion of an experimental and theoretical effort to investigate the thermodynamics of shock processes in heterogeneous mixtures.

Due to multiple wave interactions between the components in the mixture, the thermodynamic loading path may not be along a single-shock Rayleigh line and the final state may not be on the Hugoniot of the mixture. The loading path may be along a quasi-isentrope; however, the thermodynamics will depend on the length scales in the mixture. Simple and elaborate procedures for estimating the Hugoniot equation of state for material mixtures have been postulated [1] but they are based upon mass or volume averaging. In general, the complexities of impacts on heterogeneous mixtures has not been well explained. In particular, for materials like quartz and ice that have a large number of phase transitions and a significant difference in compressibility, the models are not able to fully describe the experimental data.

**Experiments:** Samples are made from a 57:43 volumetric mixture of degassed distilled $H_2O$ ice and high purity quartz sand (Mill Creek, OK, #1 Dry, U.S. Silica Co.). The constituent materials are sifted to a particle size of 125-250 μm, mechanically mixed, and cold pressed in a piston-die assembly ($<\rho>$=1.65±0.02 $g/cm^3$, 30.3×2.6 mm disc). Before pressing, the die is evacuated to approximately $10^{-2}$ Torr to reduce air in the sample. By analogous samples, the porosity is assumed to be 1.5±0.5%.

*Plate impact experiments:* Planar shock compression experiments with peak pressures of 13.2 and 16.3 GPa were performed using the 40-mm powder gun in the Harvard Shock Compression Laboratory [2]. The downrange free surface velocity was measured using interferometric velocimetry [3]. Radiance measurements were made at the downrange free surface using 0.65 and 0.81 μm silicon photodiodes and a four wavelength IR pyrometer (1.8, 2.3, 3.5, 4.8 μm) [4]. The IR pyrometer is sensitive to temperatures as low as 300 K with a time resolution of 17 ns. The experimental configuration is described in previous work [5].

As the ice-sand sample is semi-transparent in the visible and the near-IR wavelengths (0.65, 0.81, 1.8, and 2.3 μm), a method of analysis developed by Luo *et al.* [6] was used to fit the radiance data to obtain a strong constraint on the absorption coefficient and the peak radiance at each wavelength. At 3.5 and 4.8 μm, the sample is optically thick (both quartz and ice have high emissivities at these wavelengths). The radiance upon release of the shock wave is measured almost immediately after the shock reaches the free surface, and the 3.5 and 4.8 μm data are fit with a blackbody to determine the release temperatures. We neglect the release data from the visible and near-IR channels because they are dominated by the peak shock emission transmitted through the released material.

**Results:** Fitted peak radiances were obtained at λ= 0.65, 0.81, 1.8, 2.3 μm for both the high and low pressure experiments. For the 16.3 GPa experiment the apparent peak shock temperatures are [2523±11, 2351±24, 1216±24, 1047±11] K, respectively; and for the 13.2 GPa experiment the peak shock temperatures are [2479±11, 2199±118, 1149±26, 1006±13] K, respectively. Uncertainties are determined from the fitting procedure and assume an idealized experiment. The variation in temperature results from the superposition of radiation from material components at different temperatures. If the material were perfectly homogeneous the apparent temperature would be independent of wavelength. In these experiments, the ice and sand components are initially shocked to different temperatures. The time scale for thermal equilibration depends on the spatial scale of the problem. In the approximately equal volume mixture, the radiance should be dominated by the hotter component (ice).

Peak shock pressures were determined from impedence matching, using the observed shock velocity and assuming a loading path in the target along the Rayleigh line. Under this assumption, the peak pressure agrees well with a model Hugoniot based on a mass-weighted mixture of quartz [7] and $H_2O$ ice [8].

**Discussion:** In Table 1, the apparent peak shock and release temperatures in the ice-sand mixture are compared to model predictions from the 5-Phase $H_2O$ EOS [5,10]. The good agreement between the observed and predicted values supports the assumption that the radiance is dominated by the ice component. To test the robustness of this assumption, we performed a two-component analysis of the 1.8 and 2.3 μm data, varying the sand temperature and area fraction and fitting the

ice temperature. Using a reasonable range of post-shock area fraction (0.45-0.6) and shock temperature (400-1000 K) for quartz [7], the peak shock temperatures of the ice are tightly constrained to 1230±60 K and 1150±50 K for the 16.3 and 13.2 GPa pressure experiments, respectively. The two-component analysis is in good agreement (slightly higher) with the model predictions and observations (Table 1).

The uncertainties on the two-component analysis do not take into account the fact that thermal radiation from hotspots (possibly derived from trapped air) may be contributing to the radiance at these wavelengths; hence, the quoted values can be considered upper bounds. Other factors may contribute to non-ideal conditions in these experiments. Stress concentrations form at the intersection of shocks from adjacent particles. The loading path may be a multiple-step (quasi-isentropic) process rather than a single shock. And quartz crystals shocked in the x-direction are triboluminescent [9], producing a non-thermal component around 400-600 nm. Therefore, we neglected the visible wavelengths in the thermal analysis. In addition, surface roughness (on the scale of a grain size) may produce a surface with heterogeneous temperatures; however, an experiment on porous ice agreed well with continuum release temperature predictions (unpublished).

A number of simulations of the experiments have been performed using our modified version of the shock physics code CTH [10, 11]. So far, the calculated temperatures using the 5-Phase $H_2O$ EOS [5, 10] and two different $SiO_2$ EOS [12, 13] have not been in good agreement with the observations.

**Conclusions:** One interpretation of the data suggests that the radiance at 1.8 and 2.3 μm is dominated by the ice component. Under this assumption, we find the shock temperature in the ice to be in good agreement with predicted Hugoniot temperatures and would suggest that the loading is close to a single-shock Rayleigh line (for these length scales). From the deduction of a single shock Rayleigh line, we find that our method for determining a mass-weighted Hugoniot of the mixture is accurate. This work presents the first shock temperature measurements on an icy mixture.

**References:** [1] Meyers M. A. (1994) *Dynamic Behavior of Materials*, Wiley and Sons. [2] Stewart S. T. (2004) *LPSC*, #1290. [3] Barker L. M. and Hollenbach R. E. (1972) *J. Appl. Phys.* **43**, 4669. [4] Boboridis K., et al. (2003) *VDI-Bericht* **1784**, 126. [5] Stewart S. T., et al. (2008) *GRL* **35**, L23203. [6] Luo S. N. et al. (2004) *JGR* **109**, B05205. [7] Wackerle J. (1962) *J. Appl. Phys.* **33**, 922. [8] Stewart S. T. et al. (2005) *JGR* **110**, E03055. [9] Brooks W. P. (1964) *J. Appl. Phys.* **36**, 2788. [10] Senft L. E. and Stewart S. T. (2009) *MAPS*, in press. [11] Senft L. E. and Stewart S. T. (2007) *JGR* **112**, E11002. [12] Kerley, G. (1999) Report KPS99-4, Kerley Pub. Serv. [13] Melosh, H. J. (2008) *MAPS* **42**, 2079.
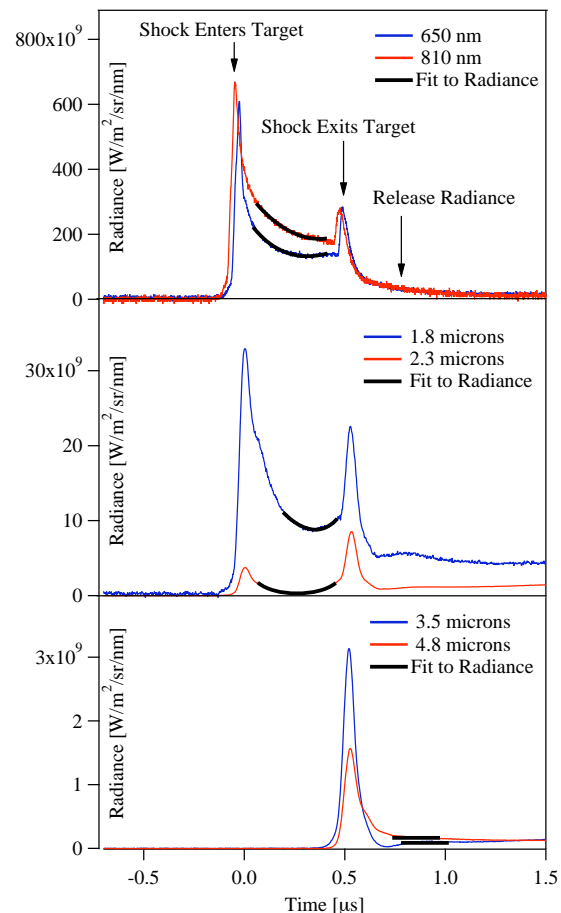


**Figure 1.** Radiance data with fits for 13.2 GPa experiment.

| Peak Shock Pressure[a] [GPa] | Apparent Shock Temp.[b] [K] | Model[c] Hugoniot Temp. [K] | Apparent Release Temp.[d] [K] | Model[c] Release Temp.[e] [K] |
|---|---|---|---|---|
| 16.3 | 1130±90 | 1145 | 630±27 | 566 |
| 13.2 | 1070±80 | 924 | 532±17 | 498 |

**Table 1.** Summary of experimental results and comparison to model equations of state.
[a]Impedance match solution. [b]Average and 1-σ error of 1.8 and 2.3 μm data. [c]5-Phase $H_2O$ EOS [5, 10]. [d]Average and 1-σ error of 3.5 and 4.8 μm data. [e]Isentropic release from peak pressure to saturation vapor curve [see 5].